GEORGIA INSTITUTE OF TECHNOLOGY

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PROJECT ADMINISTRATION DATA SHEET

Project No. E-19-649

DATE: 4/22/81

Project Director: Dr. A. P. Yoganathan

School/~~Lab~~ Chemical Engineering

Sponsor: National Science Foundation; Washington, D. C. 20550

Type Agreement: Grant No. CPE-8105152

Award Period: From 4/15/81 To 9/30/83* (Performance) -- (Reports)

Sponsor Amount: $47,970

Contracted through: GTRI/~~GIT~~

Cost Sharing: $7,750 (E-19-348)

Title: ~~Research Initiation:~~ Tubular Entry Flow of Polymeric Fluids

ADMINISTRATIVE DATA

OCA CONTACT Duane Hutchison X4820

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Reports: See Deliverable Schedule * Security Classification: None

Defense Priority Rating: None

RESTRICTIONS

See Attached Natl. Science Fdn. Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Georgia Institute of Technology

COMMENTS: *Includes the usual six (6) month unfunded flexibility period.

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date January 16, 1984

Project No. E-19-649

School/~~Lab~~ ChE

Includes Subproject No.(s)

Project Director(s) Dr. A.P. Yoganathan

GTRI / ~~GIT~~

Sponsor National Science Foundation

Title "Research Initiation: Tubular Entry Flow of Polymeric Fluids"

Effective Completion Date: 9/30/83 (Performance) 9/30/83 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Fiscal Accounting (FCTR)
- [ ] Closing Documents
- [x] Final Report of Inventions (only if positive)
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

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E-19-649

TUBULAR ENTRY FLOW OF POLYMERIC FLUIDS

Annual Progress Report (4/15/81 - 4/14/82)

Principal Investigator: Professor Ajit P. Yoganathan

I. Progress Up-to-Date:

The object of the project was to study the velocity and stress fields in tubular entry flow of polymeric fluids. The emphasis is on the role of viscoelastic rheological characteristics in determining the behavior in stable flow as well as in transition to unstable flows. Separan AP-30 was chosen as a model polymeric fluid. Due to the unavailability of a graduate student work on the grant did not commence until July 1, 1981. A student is presently working on the project for his MS thesis.

The rheological properties of Separan AP 30 (Dow Chemical Co.) in aqueous solutions of 0.5, 1.0 and 2.0 weight-percent were studied. In addition, 1.5 and 2.5 weight percent Separan solutions in a 50:50 glycerine/water mixture were also studied. Tests were conducted with a Thermal Mechanical Spectrometer (Rheometrics, Inc.) in a cone and plate geometry at a temperature of 23°C. The thermal mechanical spectrometer was used in the oscillatory mode to obtain the dynamic properties such as elastic modulus $G'(\omega)$, viscous modulus $G''(\omega)$ and dynamic viscosity $\eta^*(\omega)$ of the viscoelastic solutions. The measurements were made over three decades of frequency (0.1 to 100 radians/sec). Examples of the results obtained are shown in Figures 1-3. The results clearly show the highly viscoelastic nature of the Separan solutions. At low frequencies the viscons effects ($G''(\omega)$) appear more dominant, while at the higher frequencies the elastic effects ($G'(\omega)$) became dominant.

Rheological data was also obtained under steady state conditions, in a capillary rheometer for the 0.5, 1.0 and 2.0 weight-percent Separan solutions. This data was fitted to both Power Law and Carreau models. The experimental data and the Carreau model are shown in Figures 4 and 5. These Figures show that the Carreau model fits the data very well.

In order to perform the flow visualization and velocity measurement studies a flow loop was constructed in our polymer processing laboratory. The flow loop which is schematically shown in Figure 6 consists of: (i) 40 gallon storage tank, (ii) air-stirrer, (iii) gear pump (maximum capacity of 25 gpm), (iv) entrance section, (v) test section, (vi) flow meter and (vii) control valves. The flow loop also contains a by-pass section in order to facilitate the loading and unloading of the polymer solutions. The appropriate polymer solutions are made in 40 gallon tanks and are well stirred to ensure that the Separan AP-30 and water are properly mixed. Due to the highly viscoelastic nature of the Separan solutions, it is extremely difficult and time consuming to flush out all the air in the closed flow loop shown in Figure 6. In order to facilitate the removal of the trapped air, an air trap was built for upstream on the entrance section. With this air trap its possible to remove all the trapped air within 24 to 48 hours. At present two flow geometries have been constructed from plexiglass, namely: (i) 2:1 sudden tubular contraction (2 inch to 1 inch) and (ii) 4:1 contraction (2 inch to 0.5 inch). The construction of the flow loop together with its calibration took approximately three to four months.

Flow visualization experiments were conducted on the 2:1 contraction and have just been completed on the 4:1 geometry. A novel technique using a laser beam to produce a thin sheet of light was employed in these experiments (see Fig. 7). A brief description of the results obtained in the 2:1 geometry is given below. Flow visualization studies were conducted with 0.5, 1.0, 2.0 and 4.0 weight-percent Separan solutions. Two distinct flow regimes were identified for the stable entry flow of viscoelastic Separan solutions. A vortex growth regime and a divergent flow regime were observed at low and moderate flow rates respectively (see Figures 8-10). An unstable flow regime was observed at high flow rates, although it was not completely obvious. In the vortex growth regime, the characteristic secondary vortex which formed in the corner upstream of the small tube entrance increased in size with flow rate. The trapped secondary vortex region appeared to be completely stagnant. Velocity profile development in the entry region was smooth and continuous, and the flow appeared to be fully developed at the entrance region of the smaller tube. The divergent flow regime was characterized by an unexpected fluid deceleration at the upstream tube (i.e., larger tube) center line, while the secondary vortex decreased in size with flow rate. In the divergent flow regime the trapped vortex appeared to become active. The spiraling motion of the fluid in the vortex could easily be observed. The intensity of the spiraling motion increased with flow rate. The flow patterns exhibited large off-center line velocity maxima with local minima at the center line. As the flow rate was increased the divergent flow regime became metastable, but qualitatively it was hard to identify the instabilities. At the highest flow rate studied (900 cm^3/s) with all four Separan solutions, it was observed that the trapped vortex region was pushed almost all the way to the junction of the contraction. The length of the vortex region for the 2:1 geometry are given in Table 1.

Table 1: Vortex Length for the 2:1 Contraction

Flow Rate cm^3/s	0.5% Separan cm	1.0% Separan cm	2.0% Separan cm	4.0% Separan cm
100	1.1	1.2	1.3	1.5
300	1.8	2.0	2.1	2.5
500	2.4	2.1	1.7	1.1
900	0.9	0.7	0.5	0.4

The classic wine glass stem entry pattern was observed with all four solutions. It was observed that the vortex growth and divergent flow occurred earlier with increasing Separan concentration. Divergent flow and decrease in vortex length started occurring at a flow rate of about 300 cm^3/s with the 4.0% solution, while the same phenomena was observed with the 0.5% Separan solution at a flow rate of about 725 cm^3/s. In addition, the amount of flow divergence (i.e., off-centerline velocity maxima) were less obvious with the low concentration Separan solutions, indicating very strongly that the phenomena is due to the increase in viscoelasticity of the test fluids. The decrease in vortex length is due to fluid inertia and at the high flow rates is probably attributable to flow instability as well.

The preliminary results of the flow visualization studies on the 4:1 geometry just completed, indicate qualitatively the same phenomena as observed with the 2:1 contraction. The flow phenomena are, however, more clear and obvious. The flow instability phenomena can be clearly observed. Once instability occurs, lowering the flow rate does not cause the flow field to return to a stable state. It therefore appears that some of the instability is caused by random phenomena which once started are hard to eliminate. The flow field upstream in the entrance section appears to be stable.

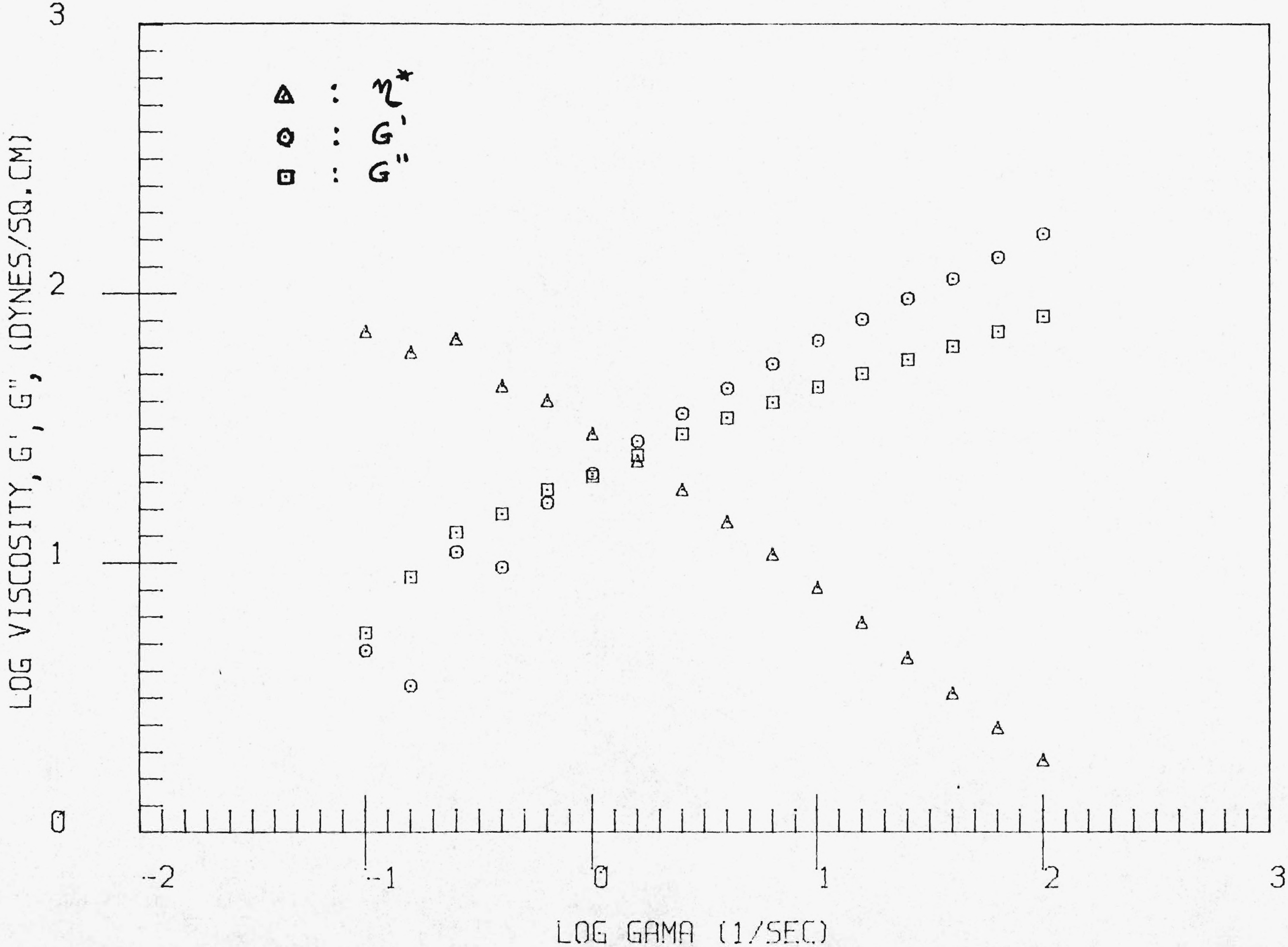
II. Problems Encountered:

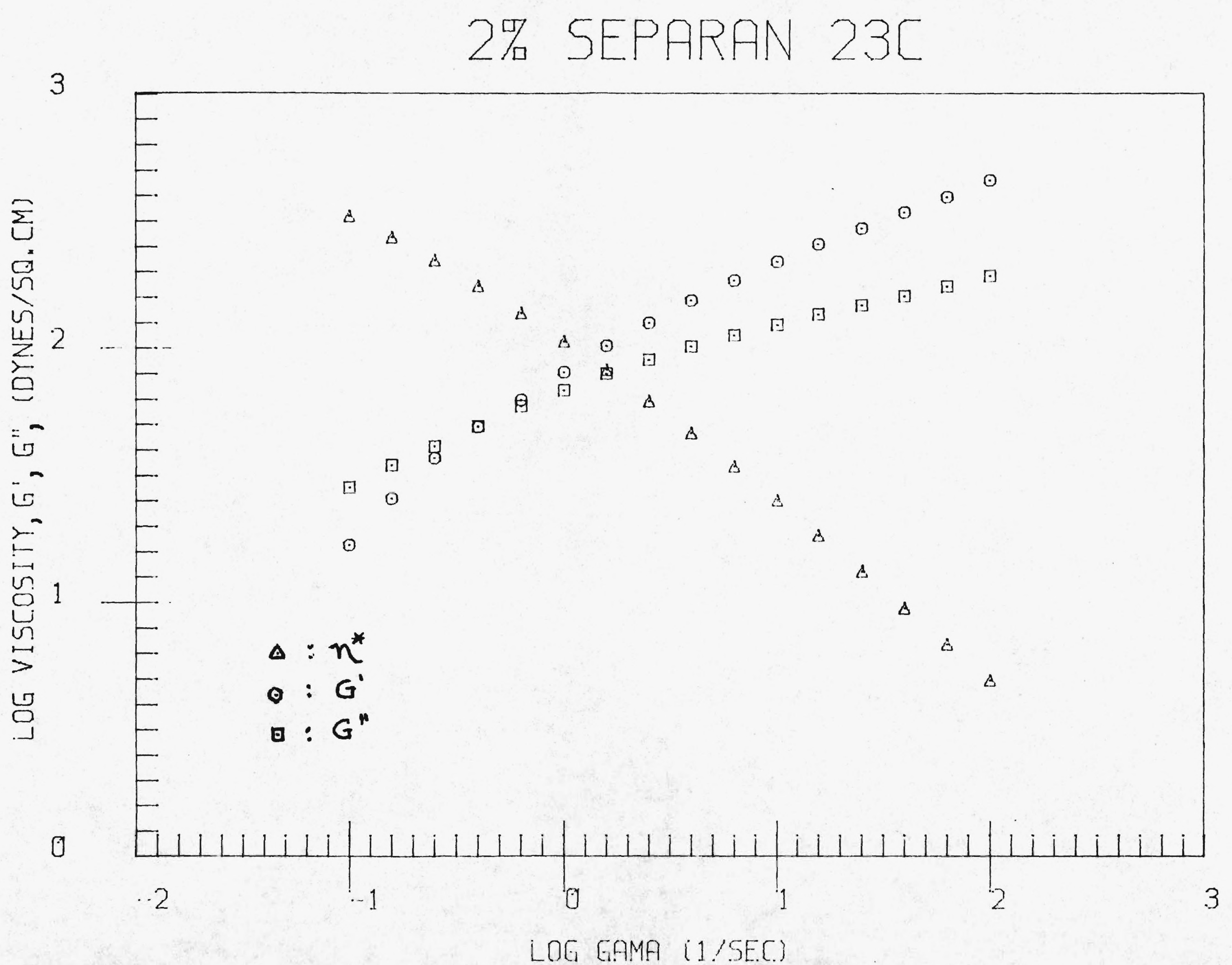
We attempted to measure or observe stress patterns in the flowing polymeric solution by utilizing well established stress birefringence techniques. Studies were conducted with both a monochromatic He-Ne laser light source and a white light source, using either plane or circularly polarized light. None of the techniques employed showed any stress patterns that could be observed by the naked eye. Similar techniques have been used by other investigators to study stress patterns in polymer melts. The techniques we used showed stress patterns in various types of plastic sheet material. The use of the techniques for studying stresses in polymer solutions has to our knowledge not been reported in the literature.

III. Future Work:

We have just started the velocity measurements on the 2:1 contraction. Detailed velocity measurements will be conducted in both geometries with the various Separan solutions and glycerine (Newtonian fluid). In doing these studies the emphasis of the measurements will be on the meta and unstable flow regions. We also plan to conduct flow visualization and velocity measurements at flow rates less than 100 cm^3/s. We will also attempt to find other methods for measuring the stress fields. If time permits the influence of entrance angle on the flow field will also be investigated.

1% SEPARAN 23C




2% SEPARAN 23C
LOG VISCOSITY, G', G", (DYNES/SQ.CM)
LOG GAMA (1/SEC)
0
1
2
3
-2
-1
0
1
2
3
Δ : η*
⊙ : G'
⊡ : G"

1.5% SEPARAN IN 50/50 GLYCERIN/WATER

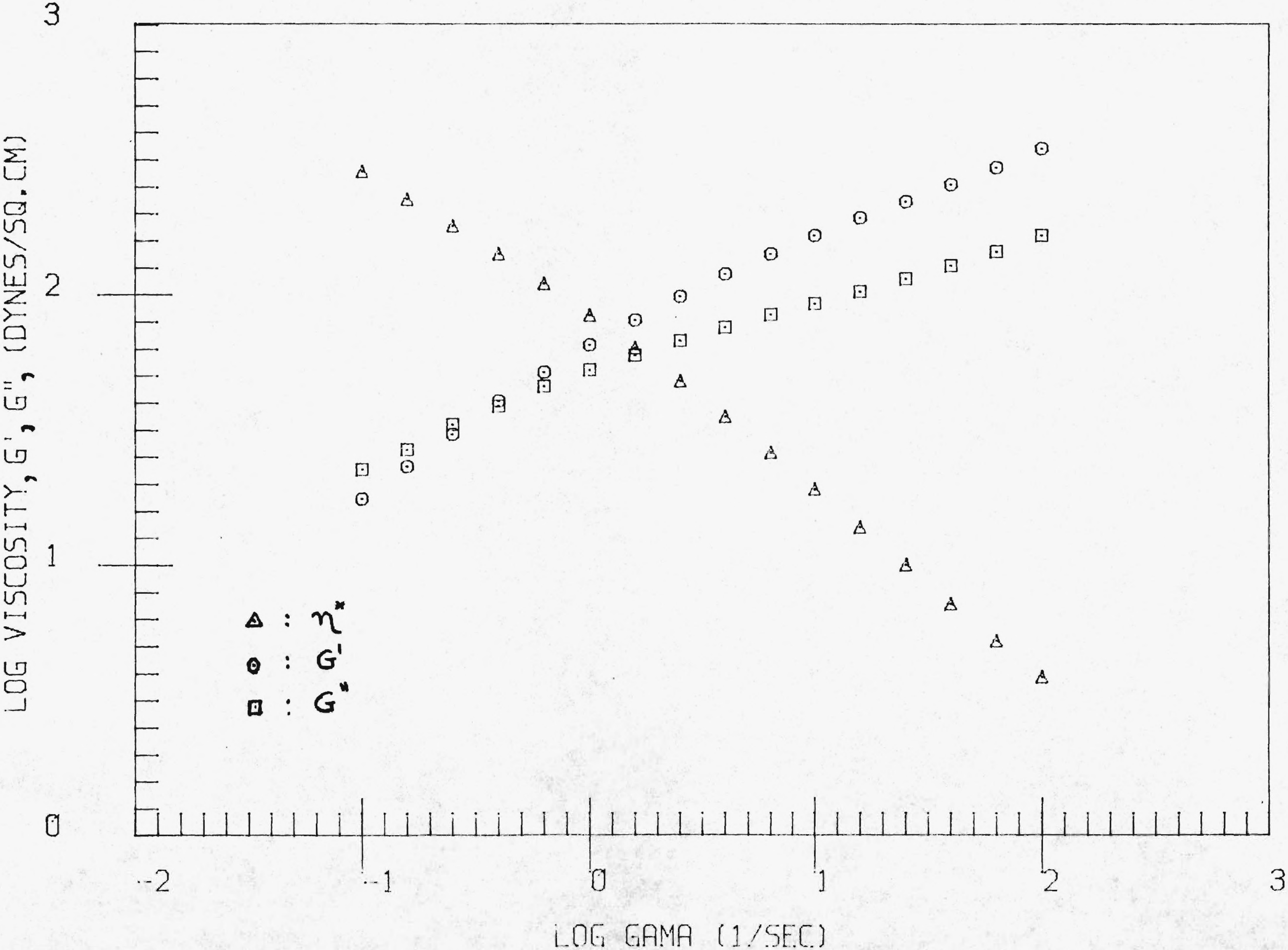
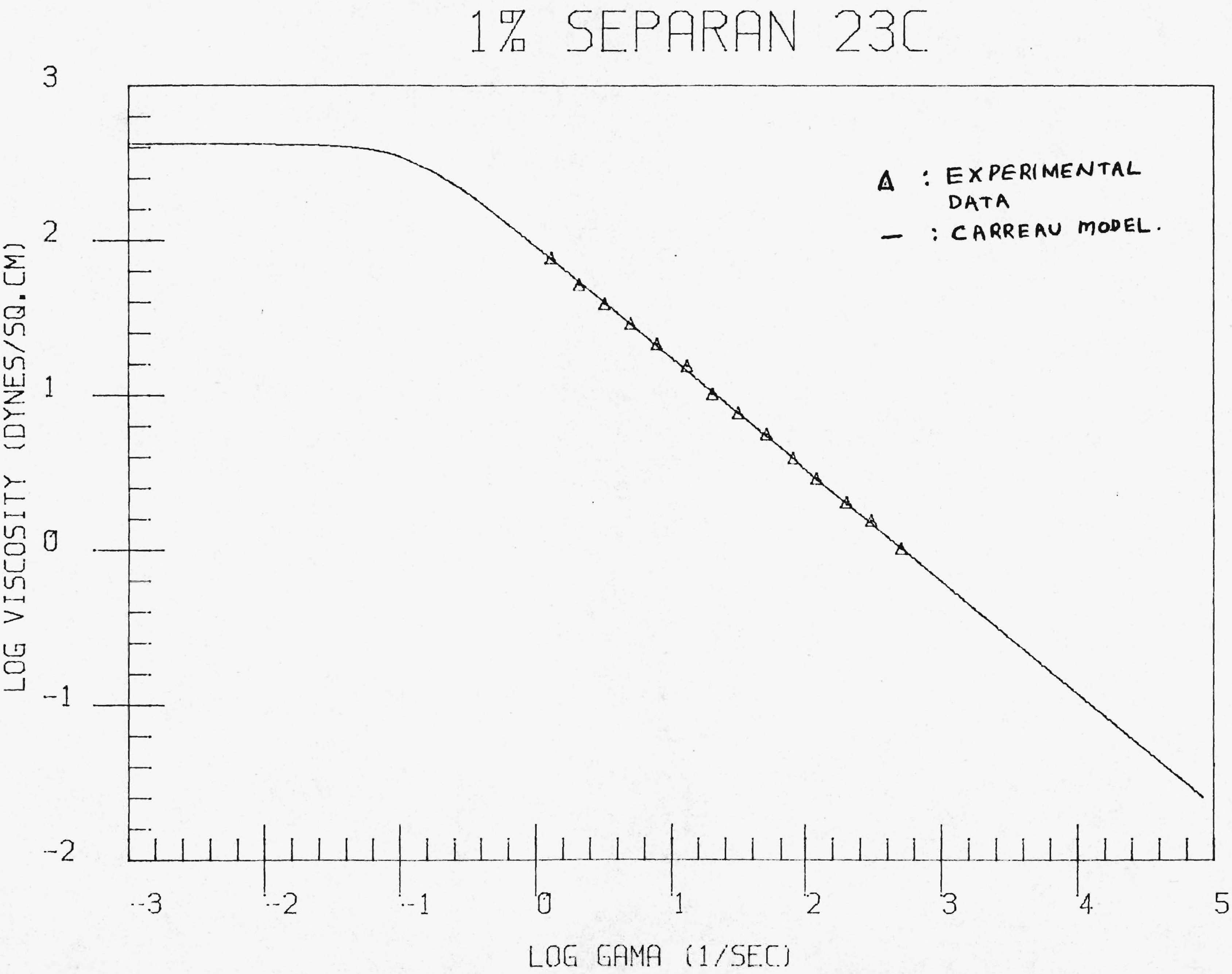
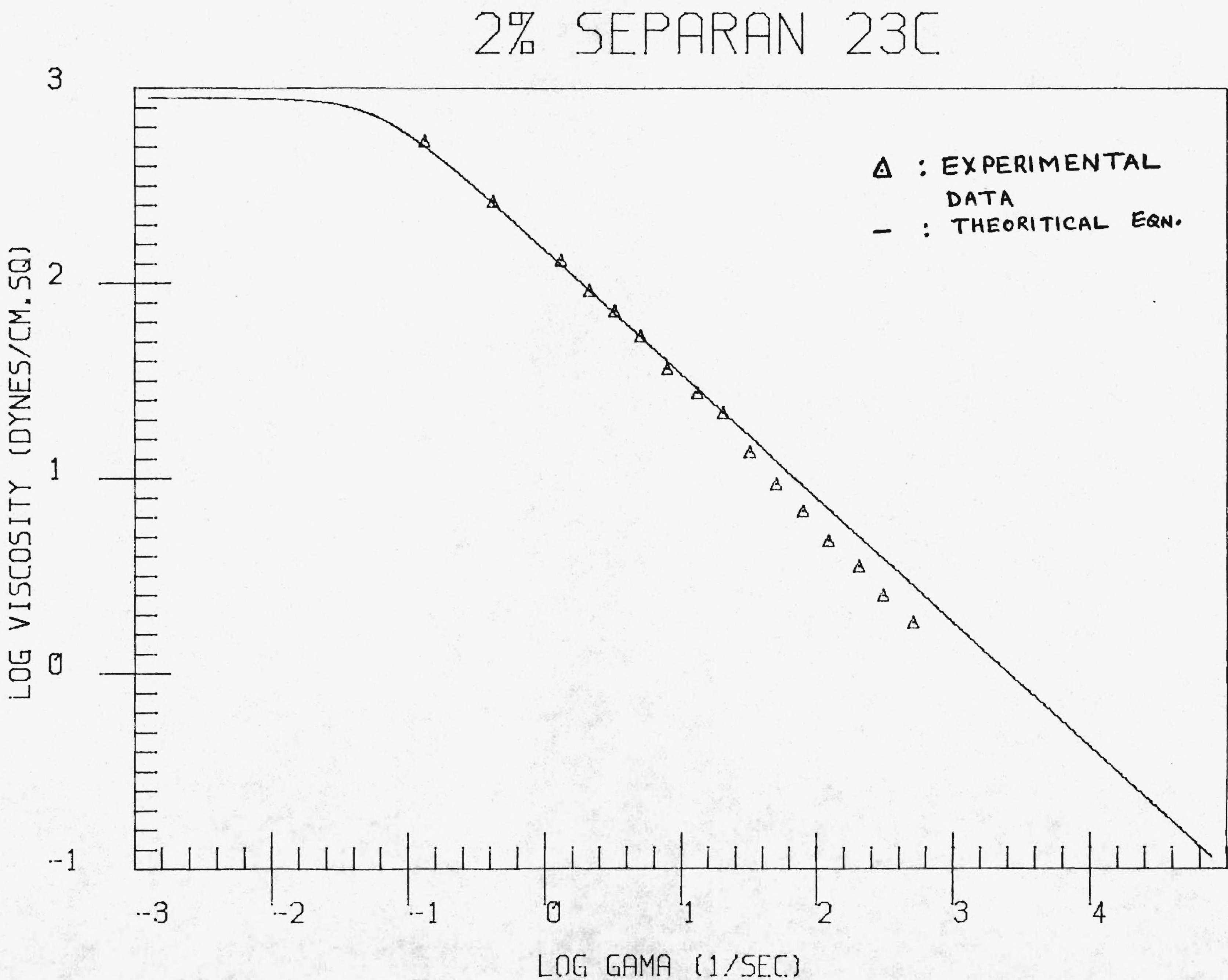
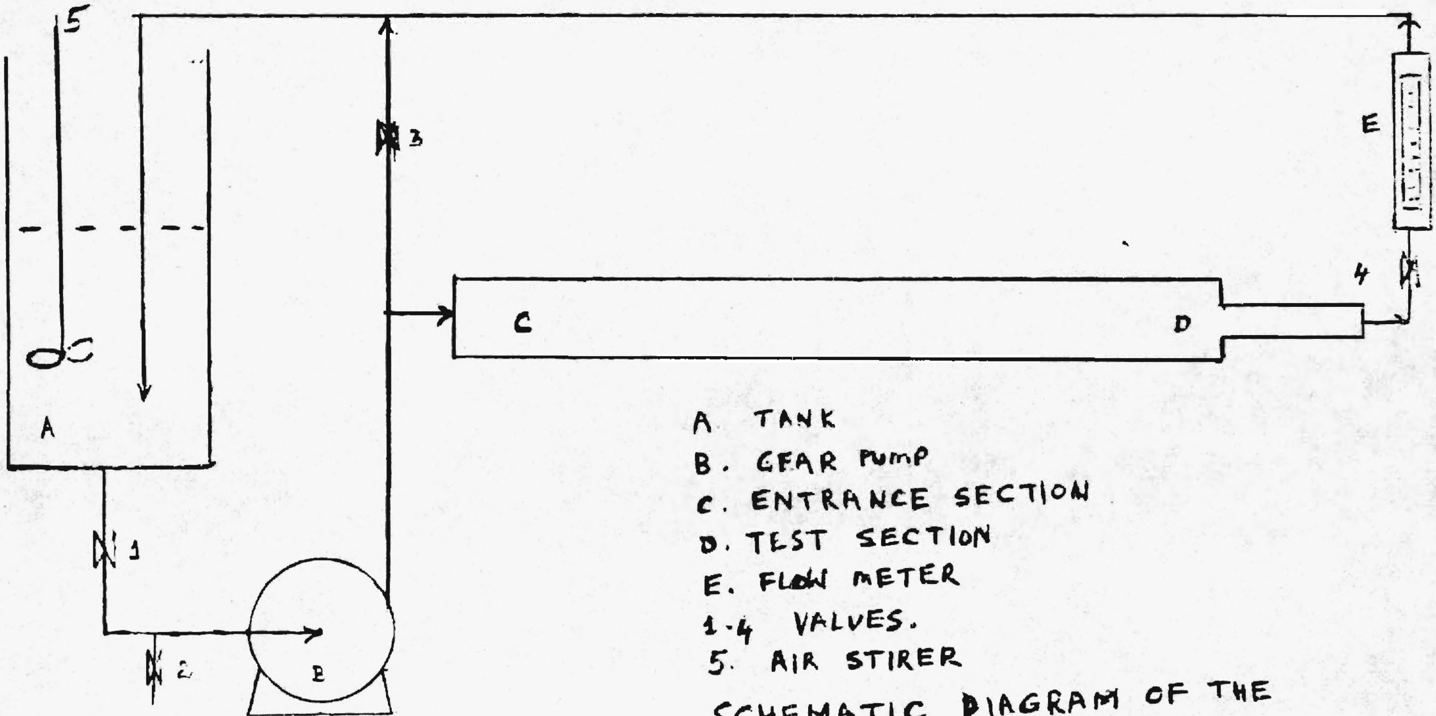


FIG. 4



1% SEPARAN 23C
3
2
1
0
-1
-2
LOG VISCOSITY (DYNES/SQ.CM)
-3
-2
-1
0
1
2
3
4
5
LOG GAMA (1/SEC)
Δ : EXPERIMENTAL DATA
— : CARREAU MODEL.

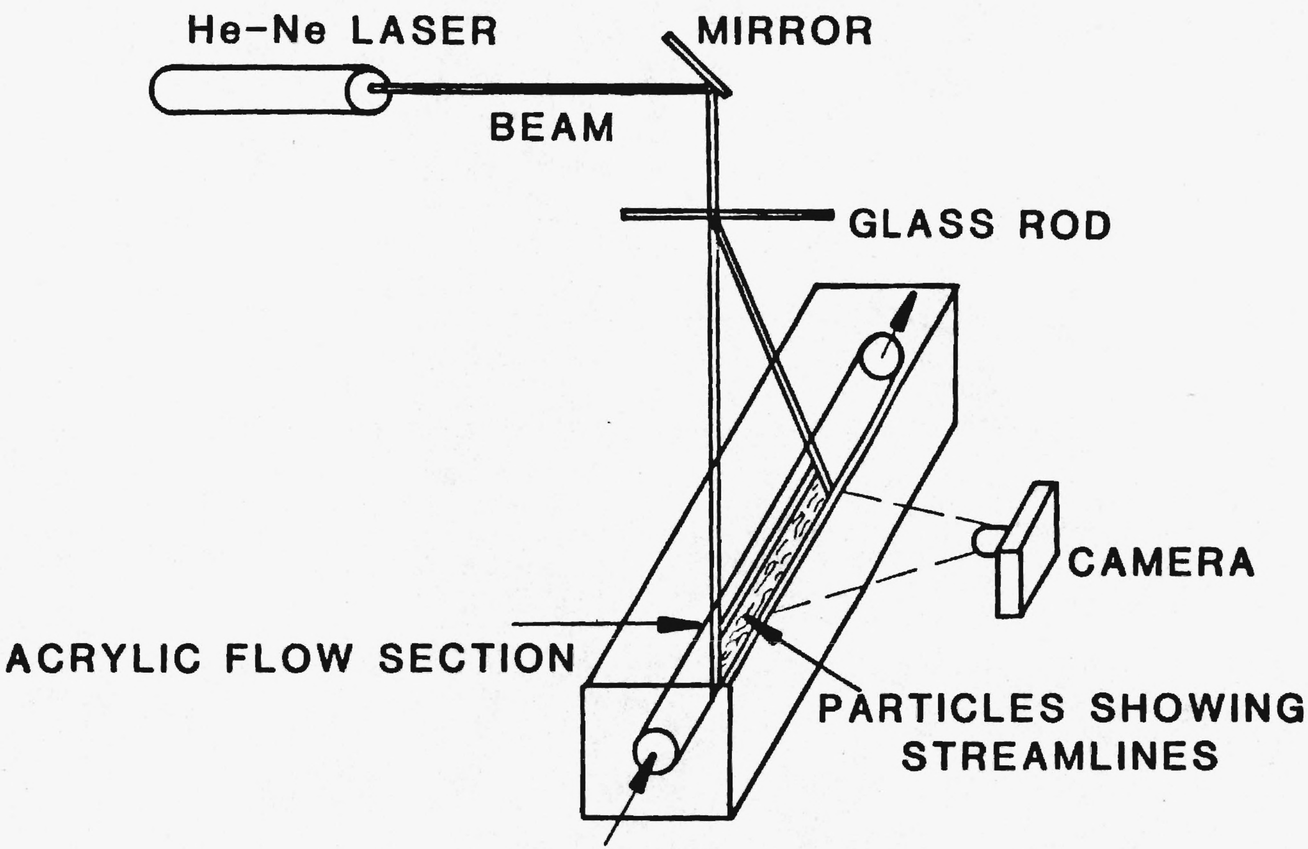

2% SEPARAN 23C
Δ : EXPERIMENTAL DATA
— : THEORITICAL EQN.
LOG VISCOSITY (DYNES/CM.SQ)
LOG GAMA (1/SEC)
3
2
1
0
-1
-3
-2
-1
0
1
2
3
4
5



A. TANK
B. GEAR PUMP
C. ENTRANCE SECTION
D. TEST SECTION
E. FLOW METER
1-4 VALVES.
5. AIR STIRER

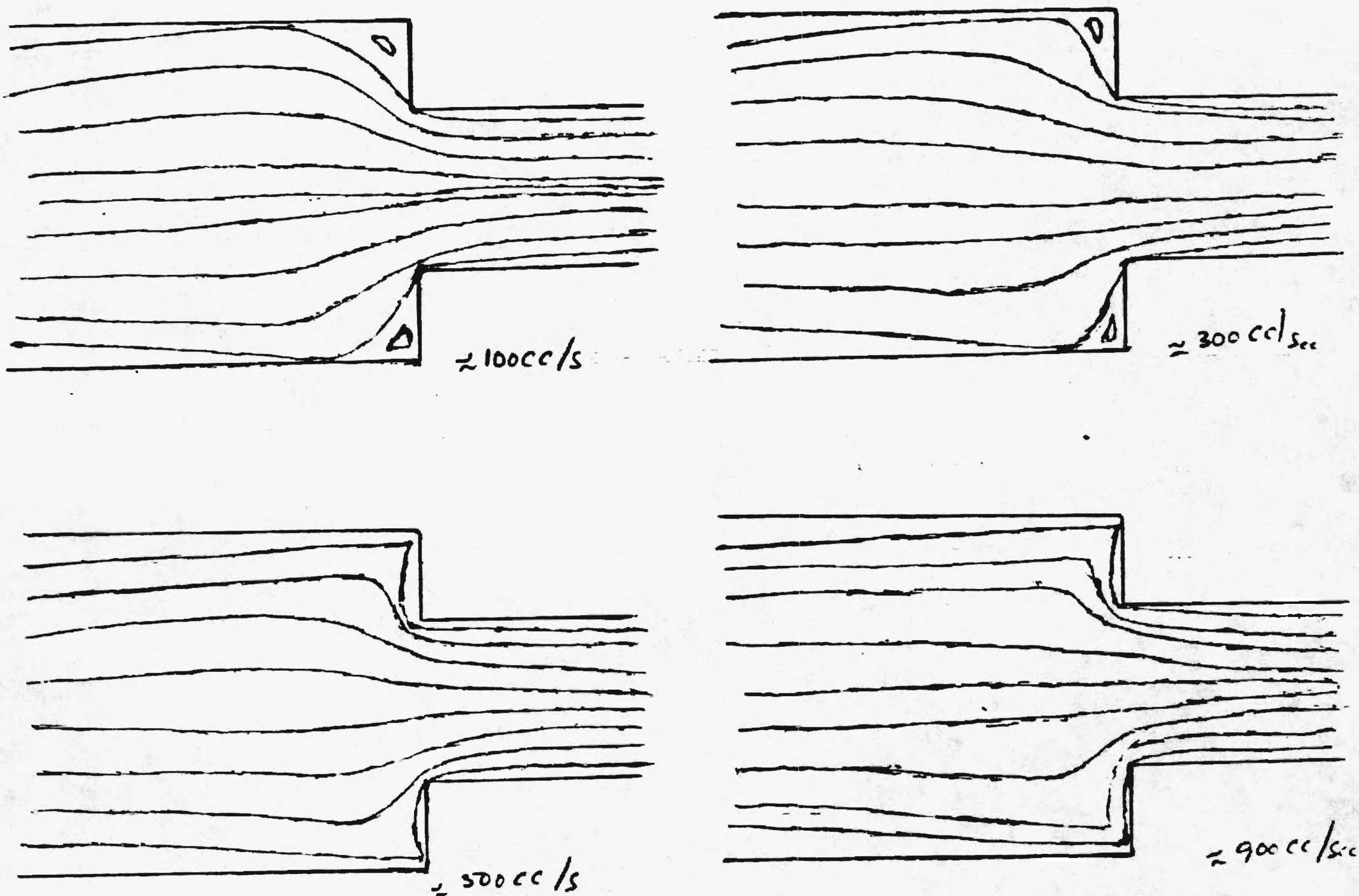
SCHEMATIC DIAGRAM OF THE FLOW SYSTEM.

FIG. 6



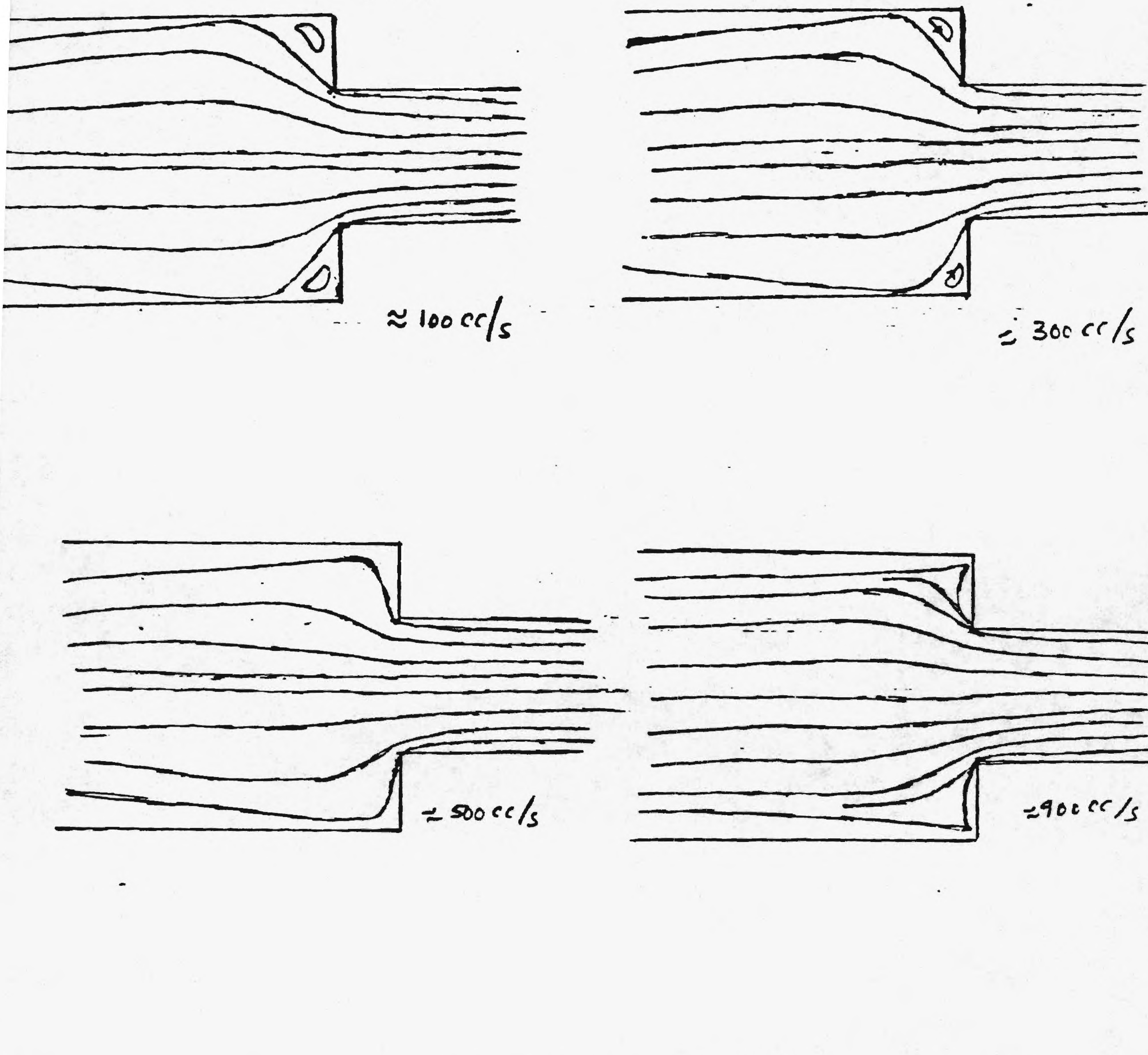
FLOW VISUALISATION SET-UP

FIG. 7



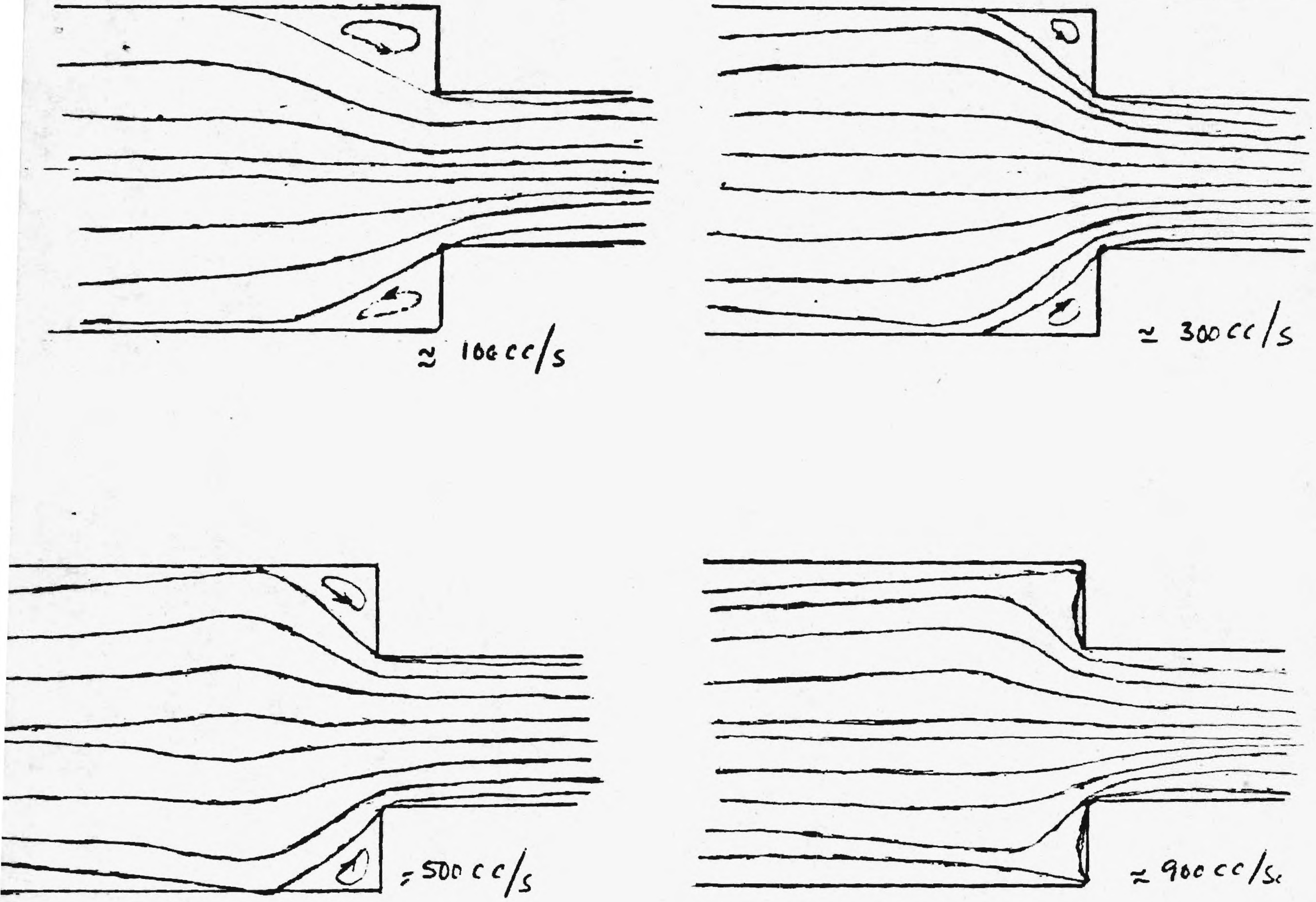
0·5% Separan Solution

FIG-8



1% Separan Solution

FIG. 9



FIG

2% Separan Solution

FIG. 10

APPENDIX VII

NATIONAL SCIENCE FOUNDATION
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FINAL PROJECT REPORT
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PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
School of Chemical Engineering Georgia Institute of Technology Atlanta, Georgia 30332	Engineering Research Initiation	CPE-8105152
	4. Award Period From 4/15/81 To 9/30/83	5. Cumulative Award Amount $47,970

6. Project Title

Tubular Entry Flow of Polymeric Fluids

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The flow fields of Separan solutions in a sudden tubular contraction were studied using both flow visualization and Laser Doppler anemometry (LDA). Aqueous Separan solutions of 2.0%, 1.0% and 0.5% by wt. were prepared and tested for their rheological characteristics, which showed their highly visco-elastic nature.

Sudden tubular contraction geometries of 2:1 and 4:1 ratios were incorporated in the flow loop constructed in the laboratory. The patterns of the flow fields were recorded using particle tracer photography. The flow patterns showed two distinct flow regimes in the stable region, which was followed by an unstable flow region. In the stable flow region a vortex growth regime and a divergent flow regime were observed. Spiralling flow was the characteristic phenomena of the unstable flow fields. The frequency of the spiralling was of the order 0.6 to 0.8 Hz.

The point velocity data were recorded using the LDA across the diameters, both upstream and downstream of the tubular contraction plane. The velocity profiles showed a third flow regime in stable flow region in addition to the two observed in flow visualization studies. The three types of flow fields observed in the steady flow region are explained considering the uneven normal stresses developed in the flow geometry and the stresses due to momentum of the flow field. The limitations involved in the analysis of unstable flow field data are explained.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	Approx. Date
a. Abstracts of Theses		X			
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c. Data on Scientific Collaborators	X				
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Ajit P. Yoganathan		11/18/83

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TUBULAR ENTRY FLOW OF POLYMERIC FLUIDS

FINAL REPORT (4/15/81 - 9/30/83)

Principal Investigator: Professor Ajit P. Yoganathan

The object of the project was to study the velocity fields in tubular entry flow of polymeric fluids. The emphasis is on the role of viscoelastic rheological characteristics in determining the behavior in stable flow as well as in transition to unstable flows. 0.5, 1.0 and 2.0 weight percent aqueous Separan AP-30 solutions were used as model polymeric fluids, in 2:1 and 4:1 sudden tubular contraction geometries.

The rheological characterization of the test fluids were conducted with a Thermo Mechanical Spectrometer in a cone and plate geometry at a temperature of 23^{o}C. Flow visualization experiments were conducted with a 7 mW He-Ne laser and 60 micron Amberlite particles. Detailed velocity field measurements were made up and down stream of the tubular contraction geometries using a three beam laser Doppler anemometer (LDA) system.

The rheological data of the Separan solutions clearly show their highly viscoelastic nature. The rheological constants obtained are comparable to the values presented in literature for similar solutions. The rheological properties of the Separan solutions are similar to those of polymer melts (such as LDPE, HDPE and polystyrene) at higher temperatures. The rheological data were used to present the experimental flow conditions in dimensionless parameters.

The following conclusions can be drawn from the present study. There are three distinct flow regimes in the stable flow region for the flow of viscoelastic fluids in a sudden tubular contraction. One, vortex growth regime, which is characterized by a smoothly converging entrance flow. In this region the length of the secondary vortex increases against the direction of the flow as the flow rate is increased. The velocity profiles are bell-shaped and center-line velocities are accelerated as the flow approaches the downstream entrance. As the flow enters the smaller diameter, it has already taken on a shape close to the developed profile. In the vortex growth regime, velocity profiles downstream of the contraction plane are totally different for the 2:1 and 4:1 contraction geometries. In the 2:1 contraction the centerline velocity profiles are overdeveloped as they enter the downstream tube, and the flow becomes redeveloped about 4 cm downstream by decelerating the center-line velocities. In contrast, for the 4:1 contraction the centerline velocities are underdeveloped, and the flow becomes redeveloped about 4 cm down stream by deceleration along the wall and acceleration near the center-line.

At moderately high flow rates, the second kind of flow regime, divergent flow, appears under favorable conditions. The solution should have enough viscoelasticity (elastic modulai should be high at these shear rates), and with the 4:1 contraction the chances of observing the presence of the divergent flow regime are more than with the 2:1 contraction. The divergent flow regime is characterized by deceleration of the center-line velocities as the flow approaches the flow detachment plane. The resultant velocity profiles are concave with off-centered velocity maxima. In this flow regime inertia effects cause the vortex length to decrease as the flow rate is increased. Uebler's effect is clearly seen in the 4:1 contraction. In the divergent flow region, if a bubble by chance tries to enter the downstream tube along the center-line, it is stopped at the entrance and remains there. Divergent flow appears only with the 2% Separan solution in the 2:1 contraction and with the 2% and 1% Separan solutions in the 4:1 contraction. The phenomena is the result of inertia effects, and the uneven normal stresses developed in the Separan solution due to shear, as the flow enters the smaller downstream tube. The divergent velocity profiles normally flatten out as the flow enters the smaller downstream tube. There is not much change in the downstream velocity profiles from that in the vortex growth region. The only exception is with the 2% Separan solution in the 4:1 contraction, where the upstream velocity profiles have high off-centered maxima. This causes the centerline velocities to be over-developed as the flow enters the downstream tube. The flow recovers within about 4 cm from the contraction plane.

The third flow regime, inertia dominating flow, was observed only at high flow rates in the 2:1 contraction with the 2% Separan solution. Its presence is confirmed in several experiments. This phenomena is characterized by the presence of a third small velocity maxima at the center-line of the tube, in addition to the divergent flow pattern. This small velocity difference is hard to identify in streak photography. The phenomena is explained on the basis of inertial forces and normal stress forces acting in opposite directions and balancing each other. The velocity profiles in the downstream tube differ from the other flow regimes recorded. At this high flow rate the disturbances of the upstream velocity field are carried into the downstream tube. A velocity profile similar to the divergent flow regime is recorded at 1.5 cm downstream of the contraction. The flow becomes developed within a distance of 4 cm downstream of the contraction.

The observed unstable flow fields appear to be analogous to those observed in traditional turbulence research. However, in turbulence research only Newtonian fluids are considered. No quantitative work has been done on the unstable flow of viscoelastic fluids. The data obtained in this study is, in our opinion, a first step in such quantitation. The observed spiralling nature of the flow fields, both upstream and downstream of the contraction plane, are definitely analogous to periodic turbulent structures. Unfortunately, at the present time we are not certain how to treat the data or know how much data to collect to conduct statistically valid analysis. This entire area of unstable flow in viscoelastic solutions and melts needs to be investigated from a fundamental point of view. This was, however, outside the scope of the present grant. It is, however, within the objectives of the overall research program to further understand the problem, and to quantitate the observed unstable flow phenomena.

It is clear from the experimental results in the stable region, that flow disturbances exist upstream of the contraction plane and are propagated downstream upto a finite distance. Observations made in the decreasing mode of flow rates showed that both the divergent flow regime and the inertia dominating flow regime are metastable. At high flow rates, the flow instabilities prevail, and remain as the flow rates are decreased. The flow field remains unstable until it reaches a flow rate low enough to establish the vortex growth regime. No other flow regimes are observed in between, giving the clear impression that the divergent and inertia dominating regimes are metastable.

THE FLOW OF VISCO-ELASTIC FLUIDS IN A SUDDEN TUBULAR CONTRACTION

A THESIS

presented to

The faculty of the Division of Graduate Studies

by

A. P. Yarlagadda

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Chemical Engineering

Georgia Institute of Technology

March, 1983

SUMMARY

The flow fields of Separan solutions in a sudden tubular contraction were studied using both flow visualization and Laser Doppler anemometry (LDA). Aqueous Separan solutions of 2.0%, 1.0% and 0.5% by wt. were prepared and tested for their rheological characteristics, which showed their highly visco-elastic nature.

Sudden tubular contraction geometries of 2:1 and 4:1 ratios were incorporated in the flow loop constructed in the laboratory. The patterns of the flow fields were recorded using particle tracer photography. The flow patterns showed two distinct flow regimes in the stable region, which was followed by a unstable flow region. In the stable flow region vortex growth regime and divergent flow regime are noticed. Spiralling flow was the characteristic phenomena of the unstable flow fields. The frequency of the spiralling was of the order 0.6 to 0.8 Hz.

The point velocity data were recorded using the LDA across the diameters, at both upstream and downstream of the tubular contraction plane. The velocity profiles showed a third flow regime in stable flow region in addition to the two observed in flow visualization studies. The three types of flow fields observed in the steay flow region are explained considering the uneven

normal stresses developed in the flow geometry and the stressess due to momentum of the flow field. The limitations involved in the analysis of unstable flow field data are explained.

. **Published Papers**

Yarlagadda, P., and Yoganathan, A. P., "The flow of viscoelastic fluids in a sudden tubular contraction," Proceedings of the 3rd International Symposium on Flow Visualization, pp. 295-299, Ann Arbor, MI, September 1983.

Yoganathan, A. P., and Yarlagadda, P., "Flow of viscoelastic fluids in a suddend tubular contraction," Proceedings of the Society of Plastic Engineers Annual Technical Conference, New Orleans, LA, April 1984.

Yoganathan, A. P., and Yarlagadda, P., "Velocity fields of viscoelastic fluids in sudden tubular contractions," submitted to the 9th International Congress on Rheology, Mexico, October 1984.

Yoganathan, A. P., Yarlagadda, P. "Flow of viscoelastic fluids in a sudden tubular contraction," currently in preparation for Journal of Non-Newtonian Fluid Mechanics.